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Life-cycle assessment of a hydrogen-based uninterruptible power supply system using renewable energy

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Abstract
Purpose The paper provides an empirical assessment of an uninterruptible power supply (UPS) system based on hydrogen technologies (HT-UPS) using renewable energy sources (RES) with regard to its environmental impacts and a comparison to a UPS system based on the internal combustion engine (ICE-UPS).
Methods For the assessment and comparison of the environmental impacts, the life-cycle assessment (LCA) method was applied, while numerical models for individual components of the UPS systems (electrolyser, storage tank, fuel cell and ICE) were developed using GaBi software. The scope of analysis was cradle-to-end of utilisation with functional unit 1 kWh of uninterrupted electricity produced. For the life-cycle inventory analysis, quantitative data was collected with on-site measurements on an experimental system, project documentation, GaBi software generic databases and literature data. The CML 2001 method was applied to evaluate the system's environmental impacts. Energy consumption of the manufacturing phase was estimated from gross value added (GVA) and the energy intensity of the industry sector in the manufacturer's country.
Results and discussion In terms of global warming (GW), acidification (A), abiotic depletion (AD) and eutrophication (E), manufacturing phase of HT-UPS accounts for more than 97 % of environmental impacts. Electrolyser in all its life-cycle phases contributes above 50 % of environmental impacts to the system's GW, A and AD. Energy return on investment (EROI) for the HT-UPS has been calculated to be 0.143 with distinction between renewable (roughly 60 %) and non-renewable energy resources inputs. HT-UPS's life-cycle GW emissions have been calculated to be 375 g of CO_2 eq per 1 kWh of uninterruptible electric energy supplied. All these values have also been calculated for the ICE-UPS and show that in terms of GW, A and AD, the ICE-UPS has bigger environmental impacts and emits 1,190 g of CO_2 eq per 1 kWh of uninterruptible electric energy supplied. Both systems have similar operation phase energy efficiency. The ICE-UPS has a higher EROI but uses almost none RES inputs.
Conclusions The comparison of two different technologies for providing UPS has shown that in all environmental impact categories, except eutrophication, the HT-UPS is the sounder system. Most of HT-UPS's environmental impacts result from the manufacturing phase. On the contrary, ICE-UPS system's environmental impacts mainly result from operational phase. Efficiency of energy conversion from electricity to hydrogen to electricity again is rather low, as is EROI, but these will likely improve as the technology matures.

Keywords Advanced energy systems · Electrolyser · EROI · Life-cycle assessment · Fuel cells · Hydrogen technologies · Renewable energy sources · Uninterruptible power supply

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1 Introduction

Due to various reasons, energy supply is becoming an increasingly popular topic. Apart from their evidently decreasing reserves, fossil fuels, which account for more than 80 % of today's total primary energy supply, also pose other problems (International Energy Agency 2011). Greenhouse gas (GHG) emissions are agreed to be the primary contributor to climate change by the majority within the scientific community. Large quantities of other toxic and harmful emissions are released

into the earth's atmosphere, soil and water during production and transport of fossil fuels, which also lead to ecological risks. Due to uneven fossil fuel deposit distribution, countries which largely depend on import are exposed to economic and political risks.

Renewable energy sources mitigate these problems to a certain degree. Solar power is available worldwide in abundance (Morton 2006) and is not available only in specific regions and in limited amounts as in the case of fossil fuels (e.g. oil). The production of electricity from renewables emits little or no greenhouse gases and pollutants during the operational phase and therefore has a lower environmental impact (Fig. 1). Furthermore, the usage of renewables poses fewer environmental risks (e.g. oil spills, emissions of radioactive materials, etc.) and is not directly affected by fuel prices set by the market.

Currently, one of the biggest challenges to the exploitation of renewable energy sources is their intermittency. The actual power supply from a photovoltaic system or a wind farm cannot be adjusted to the electricity demand. This gap has to be compensated in real time in order for the electrical grid to maintain its stability (El-Shatter et al. 2006, 2002). This can be accomplished by a system that has to be able to store electric energy very efficiently or temporarily convert it to a different energy carrier, and release it in intervals of insufficient energy supply, and in this way operate as an uninterruptible power supply (UPS) system.

UPS systems based on hydrogen technologies (HT) are considered feasible to be integrated into advanced energy supply systems on large scale (Anderson and Leach 2004; Sherif et al. 2005; Cicconardi et al. 1997). The three subsystems, electrolyser, hydrogen storage tank and fuel cell, have the ability to convert electric energy into hydrogen-based chemical energy, store it and convert it back into electricity when needed. If hydrogen is produced from renewable energy sources (RES), such a system emits very small amounts of CO_2 in its operational phase. However, in other stages of its life cycle, raw materials production, manufacturing, transport and decomposition, it is expected to have certain environmental impacts.

A life-cycle assessment (LCA) is a standardised technique to determine the environmental impacts associated with all stages of a product's life. It can also serve to improve a product's environmental profile, compare it to incumbent technology, make environmental labels and declarations, etc. Numerous scientific publications are available on hydrogen production via electrolysis using electricity from renewable energy resources (Hussain et al. 2007; Hart 2000; Koroneus et al. 2004; Cetinkaya et al. 2012), including comparisons to other hydrogen production methods. LCA of hydrogen production technologies and assembly has been carried out by several authors (Pehnt 2001; Dufour et al. 2009; Staffel and Ingram 2010; Smitkova et al. 2011; Cetinkaya et al. 2012; Patyk et al. 2013). HT in UPS applications have been evaluated without assessing their environmental performance (EPRIsolutions 2001; White et al. 2001; Vielstich et al. 2003; Rooijen Jv 2006; Wee 2007). Also, several LCA studies of HT in the context of road transport have been carried out (Hwang et al. 2013; Pereira and Coelho 2013). To our knowledge, none have assessed the environmental impacts of an

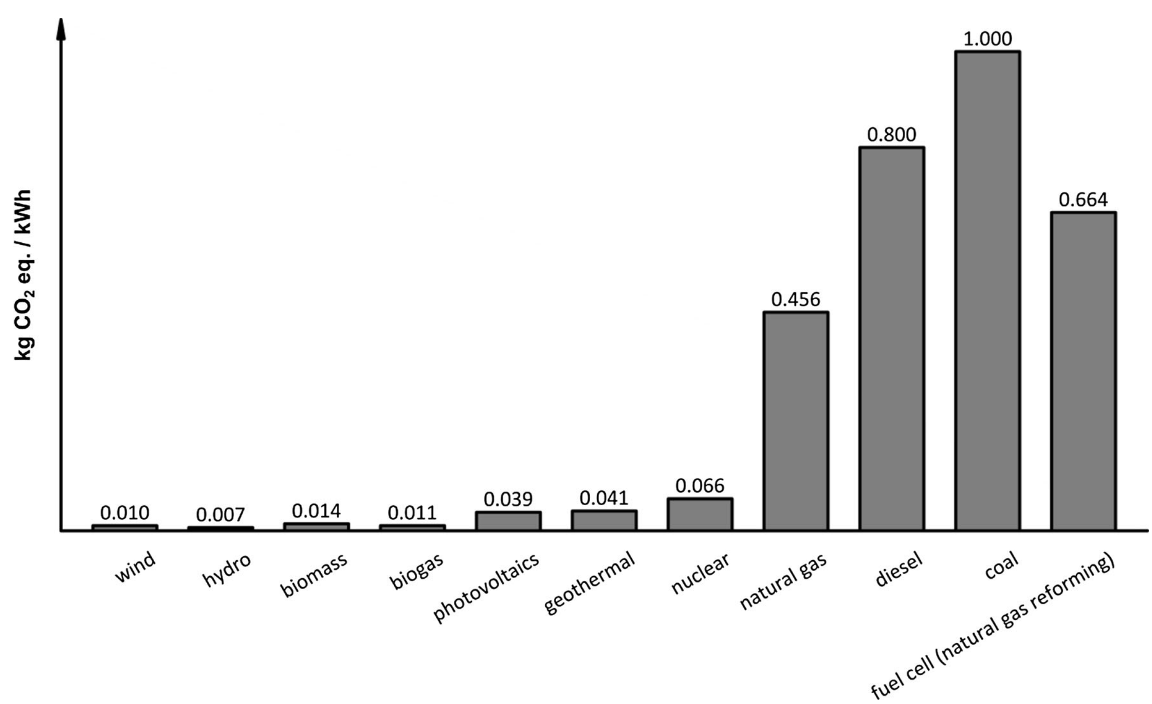


Fig. 1 Life-cycle CO_2 emissions of different technologies of electricity production and technology averages (Moomaw et al. 2011; Sovacool 2008)

actual HT-based system composed of electrolyser, hydrogen storage tank and fuel cell whose function is simultaneously energy storage and UPS, and compared it to an incumbent technology, which is the scope of this paper.

2 HT-based UPS

A combination of different HT can perform the basic functions required to maintain the stability of a power transmission grid and provide back-up power in case of primary power source shortage. An HT-UPS backup system has the potential to be an autonomous energy supplier with diverse primary energy sources and ways of production, storage and conversion of hydrogen into electricity, making it widely applicable (e.g. in road transport) and compatible with existing technologies (e.g. natural gas grid) (Ogden 1999). Hydrogen production from hydrocarbons includes natural gas reforming, coal gasification and biomass gasification and/or pyrolysis, with conversion efficiencies of up to 80, 65 and 40 %, respectively (Glavina 2008; Lotrič et al. 2011). Along with fuel cells' H_2-to-electric-energy conversion efficiency of up to 70 %, these technologies are already rivalling the efficiencies of electricity produced by common thermodynamic cycles (Milewski et al. 2010). There remain certain issues, mainly concerning the lifetime and durability of electrolytic cells, materials and capacities of storage, conversion efficiencies and price. Yet, HT are still relatively young and have seen substantial advancements through research and development in the past decade, and numerous options to overcome these issues remain to be explored.

The observed system (Fig. 2) includes an electrolyser, H_2 storage tank and a fuel cell stack with relevant support and control equipment which enables simulations and the study of HT in advanced energy systems. The system is composed of a process, support and control level (Mori et al. 2013). The scope of this study is limited to the operational level since the other two levels' only task is the simulation of RES and end-user intermittency. Technical characteristics of the system are listed in Table 1. The operating temperatures of the fuel cells are up to 80 °C, and the generated heat is considered lost. The electrolyser and fuel cell are housed in two separate standard 20-ft containers, along with the experimental equipment, while the storage tank is located outside. Only the container housing of the electrolyser is deemed necessary for the UPS's function and therefore included in the life-cycle inventory (LCI) analysis. The electrical power for the electrolyser is supplied from the grid, but controlled in a manner that imitates the RES. A representative yearly time series of available RES (solar irradiation, wind speed), calculated from multi-year averages for a specific location in Slovenia were acquired from the Slovenian Environment Agency (Slovenian Environment Agency 2008). The data was uploaded to the controller regulating the electrolyser's load. The power ratio of electrolyser to fuel cell of 10.5:1 seems large, but it has been shown that if hydrogen produced from excess RES is introduced as energy storage in advanced energy systems, the electrolyser should have a higher capacity than a fuel cell (Lacko et al. 2013, 2014). The system's characteristics are presented in Table 1.

3 LCA

LCA is the most comprehensive method for evaluating the environmental impact of the product in all its life-cycle stages. The LCA is a compilation and evaluation of material and energy inputs and outputs, and potential environmental impacts of a product during its lifetime. It consists of four stages: the definition of the goal and scope, the LCI analysis which is the construction of the product's life-cycle model where all relevant mass and energy flows are quantified, the life-cycle impact assessment which is the evaluation of the environmental relevance of these flows, and finally the interpretation of results (International Organisation for Standardisation 2006a, b).

3.1 Goal, scope and functional unit

The goal and scope define the exact questions that the analysis will try to answer and set its spatial, temporal and technological boundaries. The product's function is defined and quantified by the functional unit—which in the case of this study is 1 kWh of produced uninterrupted electricity. The goal of the study was to determine environmental impacts of the HT-UPS and compare these impacts to those of the internal combustion engine (ICE-UPS). Global warming (GW) and abiotic depletion (AD) as global, eutrophication (E) as local, and acidification (A) as regional environmental indicators were calculated and compared. The system's physical boundaries include the UPS's three subsystems: electrolyser, hydrogen storage and fuel cell (Fig. 3). A detailed presentation of the fuel cell model is shown separately in Fig. 4. The type of analysis was cradle-to-end of utilisation, covering raw materials production, energy requirements for manufacture and assembly of parts, the system's transport from manufacturing site to operation site, and its operation for 10 years. Not enough data was available to properly model the system's end-of-life phase (recycling, disposal). However, such a system predominantly consists of materials which can be recycled and used as material inputs in another product's manufacturing phase (steel, copper, aluminium, plastic materials, etc.). Equipment maintenance (all resulting material use and human labour), industry infrastructure manufacture and maintenance and land use were not considered in this study.

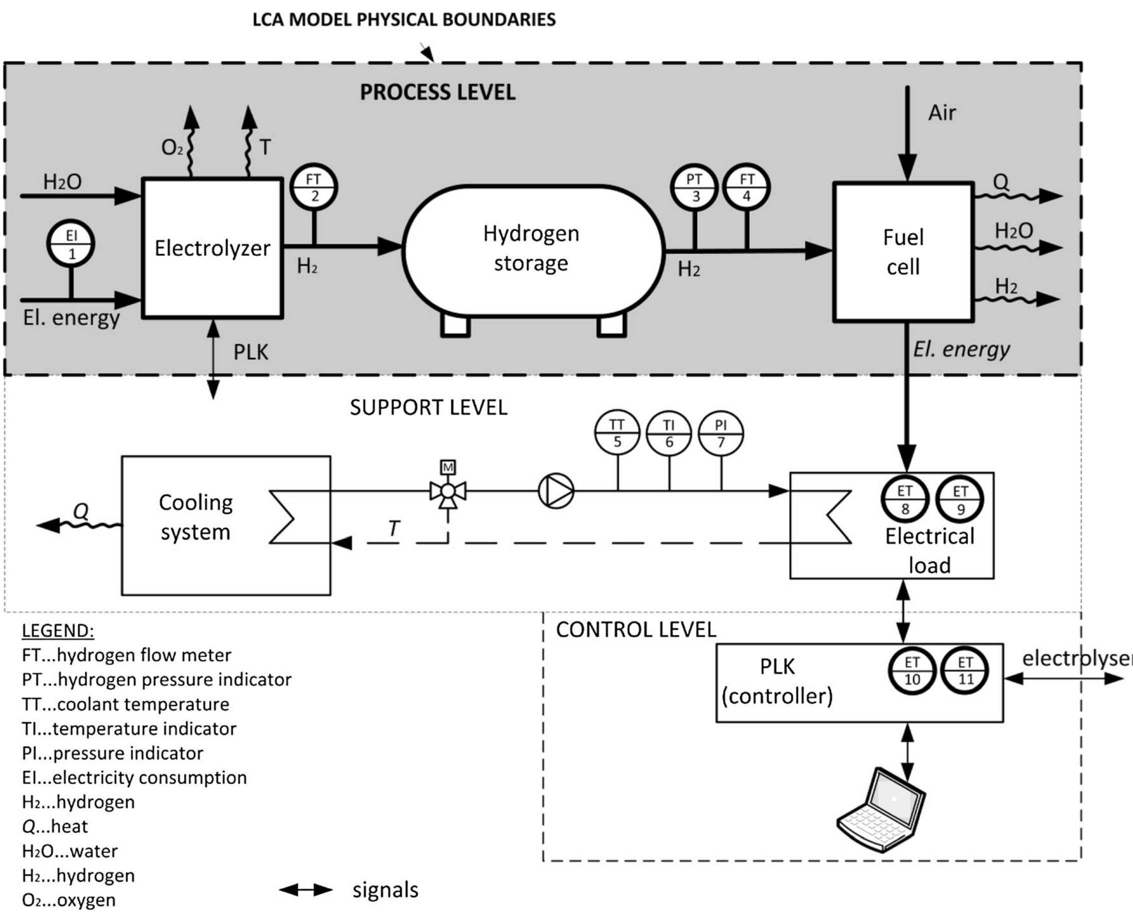


Fig. 2 Scheme of the installed HT-UPS system (Centre of Excellence for Low-Carbon Technologies 2010)

Table 1 HT-UPS technical characteristics

Electrolyser	Type	Alkaline
	Electrolyte	Water+30 $\%_m$ KOH
	Maximum power consumption	63 kW
	Hydrogen production rate	15 Nm^3/h/1.34 kg/h
	Hydrogen output pressure	6/25 bar
	Hydrogen purity (stated)	>99.99 %
	Specific energy consumption (gross measured)	6.5 kWh/Nm^3
	Efficiency—overall	0.56
	Oxygen production rate (vol)	50 % H_2 production
	Specific water consumption	<1 l/Nm^3 H_2
	Housing	20-ft container
Storage tank	Capacity	20 m^3
	Maximum operation pressure	25 bar
Fuel cell	Type	PEM
	Nominal output power	6 kW
	Maximum output power	7.5 kW
	Required hydrogen purity	>99.9 %
	Hydrogen consumption rate (stated)	0.66 Nm^3/kWh
	Specific water production	<0.66 l/kWh
	Housing	20-ft container

PEM polymer electrolyte membrane

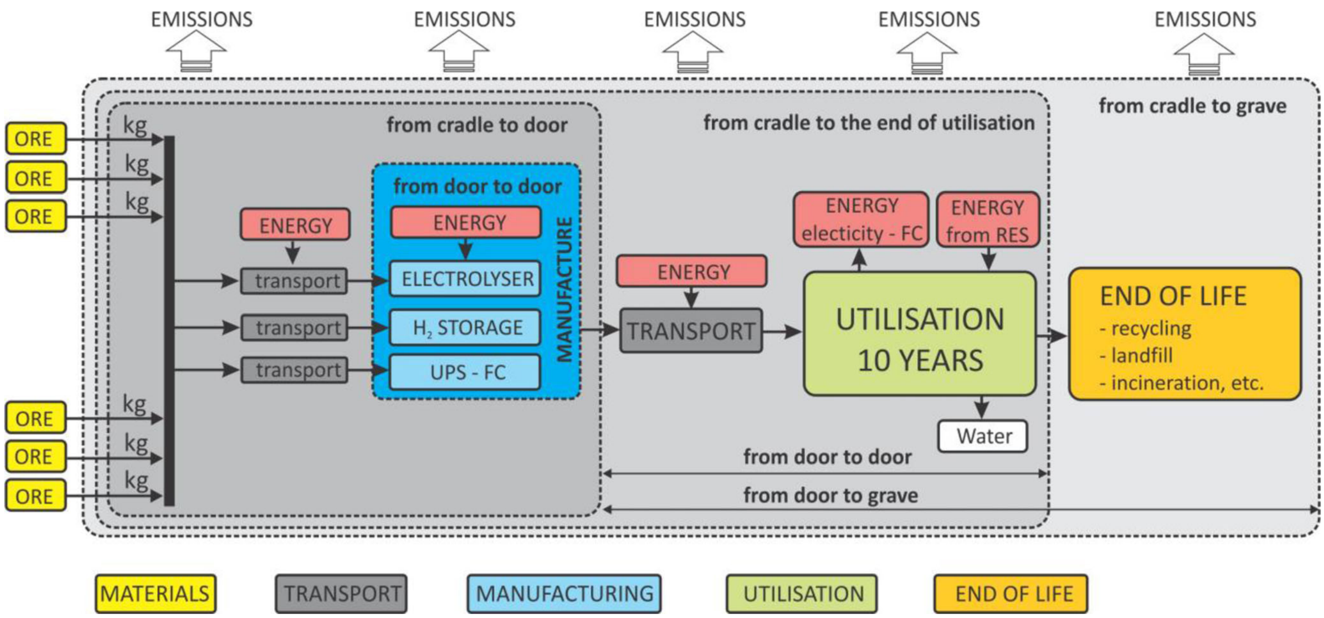


Fig. 3 General LCA model of HT-UPS system—phases, processes and flows

The same approach in LCA modelling was applied to a commercial ICE-UPS with a comparable power output. All the required quantities of used materials for the LCA numerical model (Fig. 5) were obtained from the manufacturer (Table 2). It should be noted that the ICE-UPS can only cover the shortage in RES energy supply, while the HT-UPS can also store excess RES energy in the form of hydrogen. In that respect, it should be made clear that the choice of 1 kWh of produced uninterrupted electricity as the functional unit for both systems does not mean that the two systems are equivalent. However, it enables the best comparison between the two systems studied and to other systems studied with LCA studies as they generally use the same functional unit.

A top-to-bottom principle was used to model the system, sequentially dividing it into smaller segments as far as there was available data, in order to reach the most detailed description of the system's design and function. Finally, the model had three levels with nested plans, comprised of 14 custom-made processes:

- One main integrating process
- Three system components' processes (electrolyser, storage tank and fuel cell)
- Three manufacturing processes (electrolyser, storage tank and fuel cell)
- Three transport processes (electrolyser, storage tank and fuel cell)
- Three operation processes (electrolyser, storage tank and fuel cell)
- One electrolyser's container manufacturing process

These were complemented by 13 generic processes from GaBi's professional database. The GaBi database-based generic processes include raw material production and electric

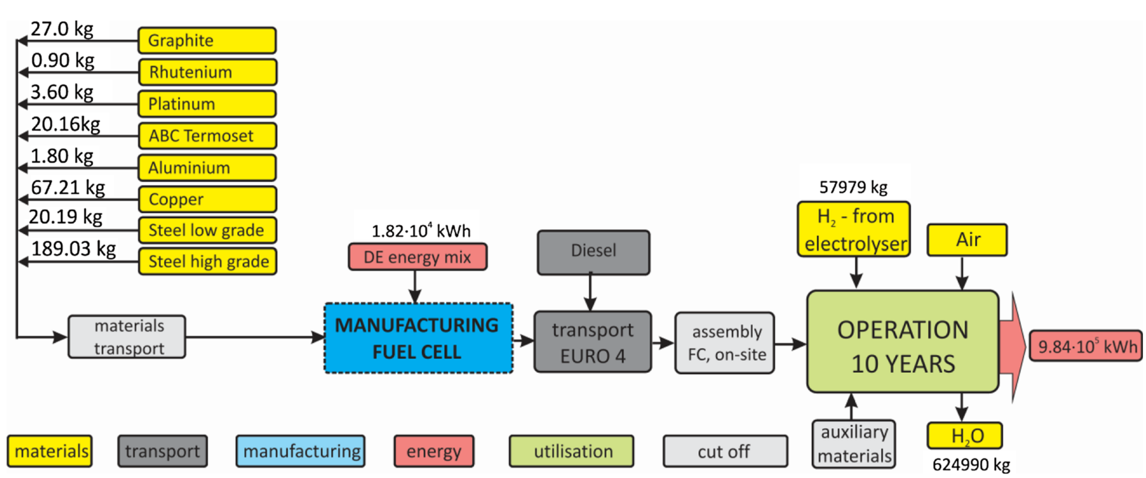


Fig. 4 LCA model of FutureE's Jupiter PEM fuel cell

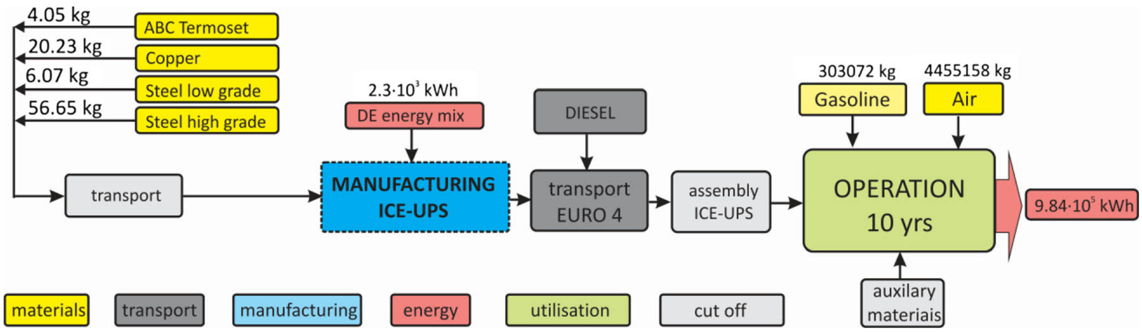


Fig. 5 LCA model of ICE-UPS system

energy mixes in the manufacturing phase, diesel production and type Euro 4 cargo trucks in the transport phase, water, KOH, hydrogen and oxygen in the operation phase and are presented in Table 3 (PE International 2012).

3.2 LCI analysis

In the inventory analysis (LCI), all relevant flows, major resources and energy consumption throughout the UPS life cycle were considered. The results are presented in Table 3. The data for the LCI was obtained from on-site measurements, project documentation, correspondence with manufacturers and literature, in that order of priority (Mori et al. 2013; Odyssee indicators 2010). LCI data were extracted from Gabi for the inputs that are stated in Table 3 (PE International 2012).

In general, quantitative data for raw materials consumption in the manufacturing process was obtained by correspondence with manufacturers and literature review. Transport data was obtained as a combination of transport distances and the GaBi generic database. Data for the operation of the UPS system was obtained from on-site measurements. Energy consumption for the manufacture and the assembly of parts was estimated from gross value added (GVA) of the produced technology and the energy intensity of the industry sector in the manufacturer's country, Eq. (1) (Jensterle 2012).

$$W^{el}_{component} = GVA_{component} \cdot EI_{country,ind.sec.} \tag{1}$$

Energy intensity (EI_i) of the country in kilowatt hour per euro is calculated on the basis of total energy consumption of the country divided by the country's GVA (Odyssee indicators 2010). Energy intensity values are 1.17463, 2.10503 and 1.34908 kWh/€ for Germany, Belgium and the UK, respectively.

$$EI_{country,ind.sec.} = \frac{W^{el}_{country,ind.sec.}}{GVA_{country,ind.sec.}} \tag{2}$$

The electrolyser's lifetime load factor (10 years) was estimated to be 0.5, in which availability of RES, hydrogen losses and maintenance time is considered. This load factor has been used in at least one previous scientific publication (Patyk et al. 2013), based solely on RES availability. The technical characteristics (Table 1) and the load factor result in 57,980 kg of H_2 produced in 10 years. With H_2, electrolysis efficiency of 0.56, $4.08 \cdot 10^6$ kWh of electrical energy is needed. Hydrogen losses from electrolyser to the atmosphere because of system conditioning amount to 11,960 kg of H_2 and contribute to environmental impacts in the UPS's operational phase (Mori et al. 2013). Almost 10^6 kg of water is used for electrolysis in 10 years (Hydrogenics 2011).

3.3 Life-cycle impact assessment (LCIA)

In the LCIA step, all input and output flows are translated into contribution to the chosen environmental impact categories (e.g. GW). For this study, the life-cycle numerical model was created using GaBi 5 software, developed by PE International GmbH (PE International 2012), which processes the LCI data according to ISO 14040. GW, AD, E and A were calculated as environmental impact indicators (Heijungs 2014) according to the CML 2001 methodology (Guinée 2002). Additionally, life-cycle energy balances, including energy return on investment (EROI), were calculated.

3.4 Life-cycle interpretation

In the life-cycle interpretation step, attention was paid to the consistency and wholeness of the analysis to determine

Table 2 Technical specifications of Wiltec SH 7500 TE-2 ICE-based UPS

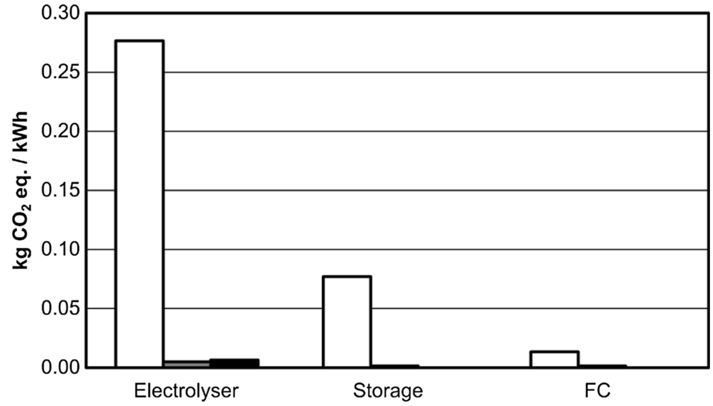
Motor type	Gasoline (4 stroke)
Volume	389 cm^3
Output power (DC)	6 kW
Nominal motor power	9.70 kW (13 HP)
Nominal output voltage	230 V/400 V
Frequency	50 Hz
Fuel	Unleaded gasoline
Specific consumption	0.308 kg/kWh_{el}

Table 3 LCI table

	Level	Type	Flow	Quantity	Quantity from
Electrolyser	Parts manufacture and assembly	Input	Steel high grade	1,400 kg	1
		Input	Steel low grade	150 kg	1
		Input	Electrolyte copper	500 kg	1
		Input	Nickel	50 kg	1
		Input	Abs thermoset	100 kg	1
		Input	Platinum	5 kg	1
		Input	Electricity—grid mix—Belgium	6.58×10^{5} kWh	2
	Container manufacture	Input	Steel high grade	2,230 kg	1
		Input	Electricity—grid mix—UK	970 kWh	2
	Transport	Input	Diesel	1,366 kg	1
	Operation	Input	Water	937,484 kg	2
		Input	KOH	160 kg	2
		Input	Electricity—grid mix—EU renewables	4.08×10^{6} kWh	2
		Output	Hydrogen (useful)	57,980 kg	2
		Output	Hydrogen (losses)	11,960 kg	2
		Output	Oxygen	554,991 kg	2
Storage tank	Manufacture	Input	Steel high grade	16,964 kg	1
	Transport	Input	Diesel	22.7 kg	1
	Operation	Input	Hydrogen	57,980 kg	2
		Output	Hydrogen	57,980 kg	2
Fuel cell	Parts manufacture and assembly	Input	Steel high grade	189.03 kg	1
		Input	Steel low grade	20.9 kg	1
		Input	Electrolyte copper	67.21 kg	1
		Input	Aluminium	1.80 kg	1
		Input	Abs thermoset	20.16 kg	1
		Input	Platinum	3.60 kg	1
		Input	Ruthenium	0.90 kg	1
		Input	Graphite	27.00 kg	1
		Input	Electricity—grid mix—Germany	1.82×10^{4} kWh	2
	Transport	Input	Diesel	9.1 kg	1
	Operation	Input	Hydrogen	57,980 kg	1, 2
		Input	Oxygen	554,991 kg	1, 2
		Output	Electricity—renewable	9.84×10^{6} kWh	1, 2
		Output	Water	624,990 kg	1, 2
ICE	Manufacture	Input	Steel high grade	56.56 kg	1
		Input	Steel low grade	6.07 kg	1
		Input	Copper	20.23 kg	1
		Input	Abs thermoset	4.05 kg	1
		Input	Electricity—grid mix—Germany	2.3×10^{3} kWh	2
	Transport	Input	Diesel	3.2 kg	1
	Operation	Input	Gasoline	303,072 kg	2
		Input	Oxygen	4,455,158 kg	2
		Output	Electricity	$9.84°10^{6}$ kWh	2

1 correspondence with manufacturer, *2* experimentally determined/calculated, *ICE* internal combustion engine

whether the methods, models and data are consistent with the goals of the analysis. To ensure the credibility and comparability of such analyses, standardisation documents have to be taken into account. Since 1997, ISO standards 14040 and 14044 have covered terminology, methods and procedures, environmental declarations, resource management,



	Electrolyser	Storage	FC
manufacturing	2.73E-01	7.72E-02	1.34E-02
transport	4.98E-03	8.15E-05	3.29E-05
operation, 10 years	6.18E-03	0.00	0.00

Fig. 6 Global warming (CML2001—100 years, kg CO_2 eq/kWh) for HT-UPS system

measurements and audits (International Organisation for Standardisation 2006a, b). The two technologies that were studied in this paper were compared in terms of chosen environmental indicators, and major contributors to environmental impacts were identified.

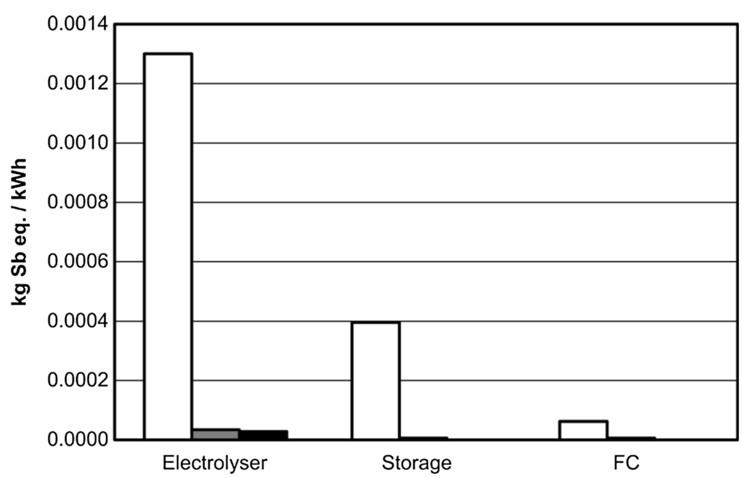
4 Results and discussion

Results are divided into three areas: In Chap. 4.1, the environmental impacts of the HT-UPS are presented in four categories according to CML 2001 (GW, AD, A and E) with respect to the system's life-cycle stages where they occur. In chapter 4.2, EROI of the HT-UPS is presented, with distinction between renewable and non-renewable energy resources inputs. In chapter 4.3, a comparison to the ICE-UPS is made in terms of the four categories of environmental impacts and EROI.

4.1 CML 2001 impact categories

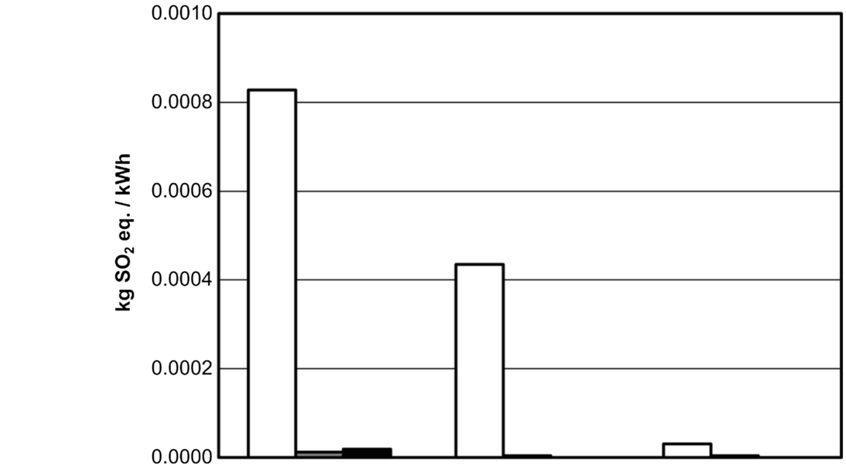
Figure 6 shows the technology's life-cycle GW impact in all its relevant phases. Although GW amounts to 368,852 kg CO_2 eq in total, or 0.38 kg CO_2 eq/kWh, it is evident that most of this impact, 97 %, results from components' manufacturing, just 2 % from transport and just 1 % from operation (Fig. 6). A look at the system's components' contribution to the total GW reveals that the electrolyser's impact is prevalent and accounts for almost 76 % (279,565 kg CO_2 eq, or 0.28 CO_2 eq/kWh) of the entire GW (368,852 kg CO_2 eq). The results also show that from the GW perspective, a HT-UPS system powered by RES electricity generally has a smaller environmental impact per kilowatt hour of uninterruptible electric energy delivered than a UPS fuel cell system with a natural gas reformer (Fig. 1).

AD impact (Fig. 7) and A impact (Fig. 8) show the same pattern despite the fact that AD is a global and A is a regional impact criterion. The manufacturing part of the HT-UPS



	Electrolyser	Storage	FC
manufacturing	1.30E-03	3.96E-04	6.24E-05
transport	3.35E-05	5.49E-07	2.24E-07
operation, 10 years	2.75E-05	0.00	0.00

Fig. 7 Abiotic depletion (CML2001, kg Sb eq/kWh) for HT-UPS system



	Electrolyser	Storage	FC
manufacturing	8.28E-04	4.34E-04	3.04E-05
transport	1.25E-05	3.25E-07	1.12E-07
operation, 10 years	1.81E-05	0.00	0.00

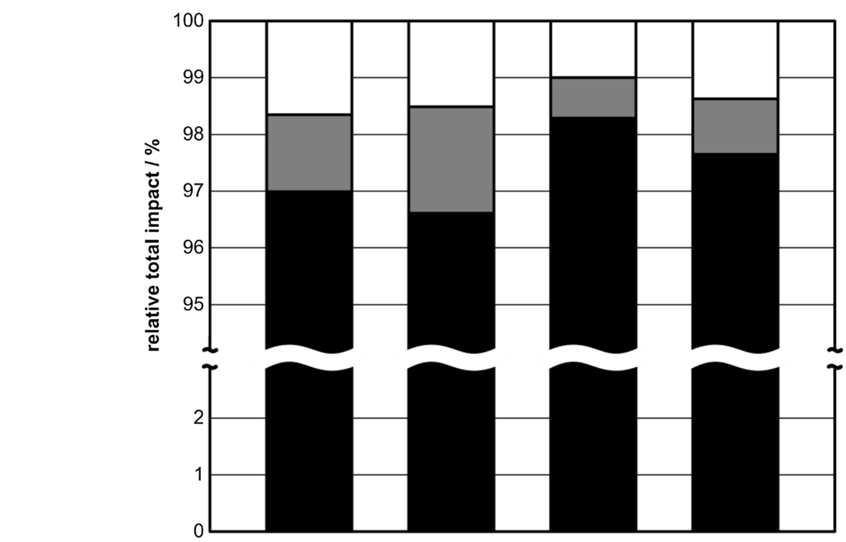
Fig. 8 Acidification (CML2001, kg SO_2 eq/kWh) for HT-UPS system

system contributes the most environmental impact in all observed categories (Fig. 9).

Figure 7 shows that the total value of HT-UPS's AD stands at 1,788.6 kg Sb eq, of which 71 % is the result of electric energy production and 25 % of steel production. For all components, the impact of transport and operation phases is low (2.5 % of transport and 2 % of operation of the total value of 1,336.4 kg Sb eq for electrolyser; 0.1 % of transport and 0 % of operation of the total 390.55 kg Sb eq for tank storage; 0.4 % of transport and 0 % of operation of total 61.65 kg Sb eq for fuel cell), while the impact of manufacturing phase is prevalent (more than 99 % of total AD is due to storage tank and the fuel cell manufacturing).

Figure 8 shows A impact of the HT-UPS system for all life-cycle stages and components. Steel production (39 % of total A impact) and electricity production (58 %) contribute the most to A impact. Almost 98 % of total A results from the manufacturing phase with electrolyser accounting for the highest contribution (65 % of UPS's total A), as shown in Fig. 8.

The total value of the E impact, 275.48 kg PO_4 eq, is mostly due to steel production phase (72.5 %), where the storage tank manufacturing phase has the highest impact (Fig. 10). If we look at the HT-UPS's components' contributions, the electrolyser is the biggest contributor in all impact categories except in E, where the impact of the storage tank



	GW	AD	E	A
operation, 10 years	6.18E-03	2.75E-05	2.79E-06	1.81E-05
transport	5.09E-03	3.43E-05	2.00E-06	1.29E-05
manufacturing	3.64E-01	1.76E-03	2.75E-04	1.29E-03

Fig. 9 The contribution of phases in observed CML2001 impact categories for HT-UPS system

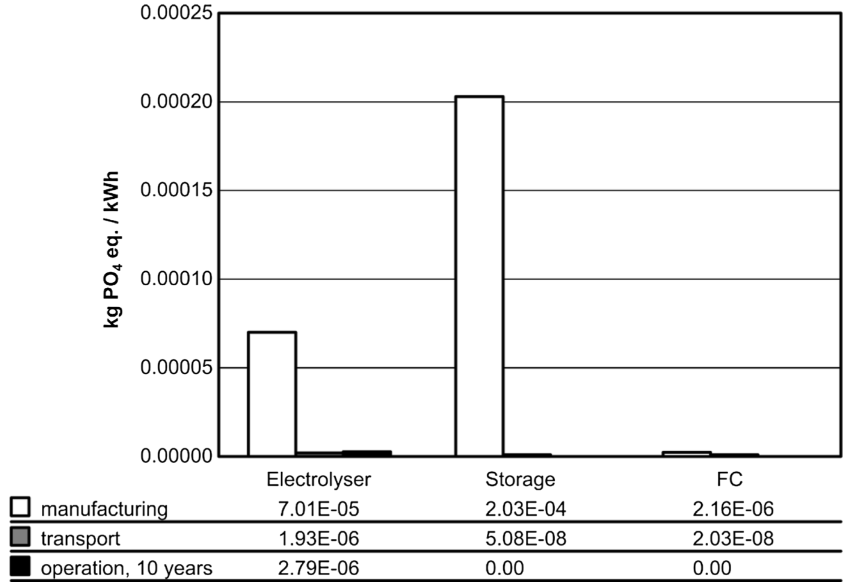


Fig. 10 Eutrophication (CML2001, kg PO_4 eq/kWh) for HT-UPS system

manufacturing phase prevails due to production of large quantities of steel (Figs. 6, 7, 8 and 10). The electrolyser's impacts are higher than those of the fuel cell mainly due to the former's higher capacity and subsequently larger material and energy inputs in the manufacturing phase.

4.2 Energy efficiency of HT-UPS system

Energy inputs presented in Table 4 are obtained from the LCA model (Fig. 3). Energy resources are required in all life-cycle phases (raw material extraction, manufacturing phase and in transport phase), whereas in operational phase, energy output in the form of uninterruptible electricity also takes place. The HT-UPS system produces 9.84×10^5 kWh electricity in its lifetime of 10 years, calculated on the basis of technical specifications (Table 1), operating availability 0.5, maintenance requirements and measured operational data.

The total energy input for manufacturing, transport and 10-year operation of the HT-UPS system amounts to 6.89×10^6 kWh, of which 60.3 % (4.16×10^6 kWh) is produced from RES (Table 4). Ninety-eight percent (4,078,845 kWh) of RES energy is used by the electrolyser for hydrogen production i.e. electrolyser operation phase. The majority of non-renewable grid-mix energy input (2.74×10^6 kWh or 39.7 % of total energy input) results from manufacturing phase of the electrolyser, storage tank and fuel cell (98.5 % or 2,694,895 kWh of non-RES energy). In the manufacturing phase of the system, the biggest energy consumption is the electrolyser's manufacturing phase (86.0 %).

The operation phase efficiency of the HT-UPS system is calculated to be 24.1 %, Eq. (3), where W_{oper}^{FC} is electrical energy produced by HT-UPS system i.e. fuel cell and W_{oper}^{el} electrical energy required for hydrogen production in electrolyser.

$$\eta_{oper} = \frac{W_{oper}^{FC}}{W_{oper}^{el}} = \frac{9.84\cdot10^5 \text{ kWh}}{4.08\cdot10^6 \text{ kWh}} \tag{3}$$

Table 4 Input energy of HT-UPS system in its life cycle, in kilowatt hour

Source	Process	Electrolyser	Storage tank	FC	Total	% of overall		% of source	
RES	Manufacturing	39,034	35,557	3,135	77,726	1.1	60.3	1.8	100.0
	Transport	26	0	0	26	0.0		0.0	
	Operation	4,078,845	0	0	4,078,845	59.2		98.2	
	SUM_{RES}	4,117,905	35,557	3,135	4,156,597				
Grid mix	Manufacturing	2,336,330	297,943	60,622	2,694,895	39.1	39.7	98.4	100.0
	Transport	20,518	337	136	20,991	0.3		0.8	
	Operation	19,345	0	0	19,345	0.3		0.8	
	$SUM_{GRID\ MIX}$	2,376,193	298,280	60,758	2,735,231				
SUM		6,494,098	333,837	63,893	6,891,828	100.0			

RES renewable energy sources

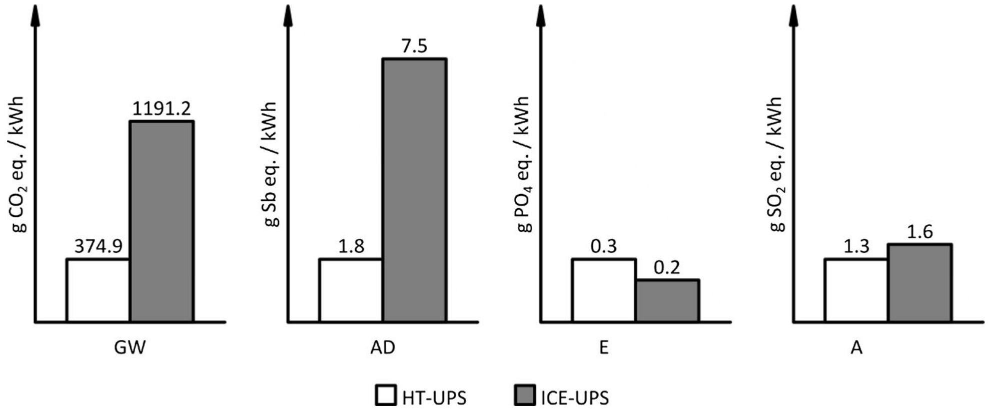


Fig. 11 Environmental impacts of HT-UPS and ICE-UPS per 1 kWh of produced uninterrupted electricity

If all energy needed in the manufacturing phase of the UPS system is included in the energy balance, the efficiency drops to 14.3 % and can be named EROI (Barnhart et al. 2013).

$$EROI = \frac{W_{oper}^{FC}}{W_{life}^{SYS}} = \frac{9.84 \cdot 10^5 \ \text{kWh}}{6.89 \cdot 10^6 \ \text{kWh}} = 0.143 \tag{4}$$

4.3 Comparison of HT-based and ICE-based UPS system

As an alternative to the HT-UPS system, the ICE-based UPS system was chosen with equal output power as the HT-UPS (Table 2). For the production of the same amount of energy as the HT-UPS in 10 years, the ICE-UPS system consumes 303,072 kg of fuel. Figure 11 shows environmental impacts of both systems. Ratios of values calculated for ICE-UPS in comparison to HT-UPS in GW, AD, E and A impact categories are 3.18, 4.15, 0.54 and 1.24, respectively. In three out of the four categories, the HT-UPS shows lower environmental impacts. HT-UPS is a relatively young technology where most of the impacts result from the manufacture and can be expected to be considerably reduced by technical progress in the future. In E impact category, HT-UPS system has a higher impact due to high electricity and material consumption (steel) in the manufacturing phase (Fig. 11).

EROI comparison shows that ICE-UPS uses less total primary energy input per kilowatt hour of uninterruptible electricity delivered at 4.72 kWh/kWh$_{el}$ compared to 7.00 kWh/kWh$_{el}$ with HT-UPS (ratio 1.48). But, a look at the energy inputs structure (RES vs. non-RES) reveals that a maximum of 0.2 % only is provided from RES in the case of ICE-UPS compared to roughly 60 % in the case of HT-UPS system (Fig. 12).

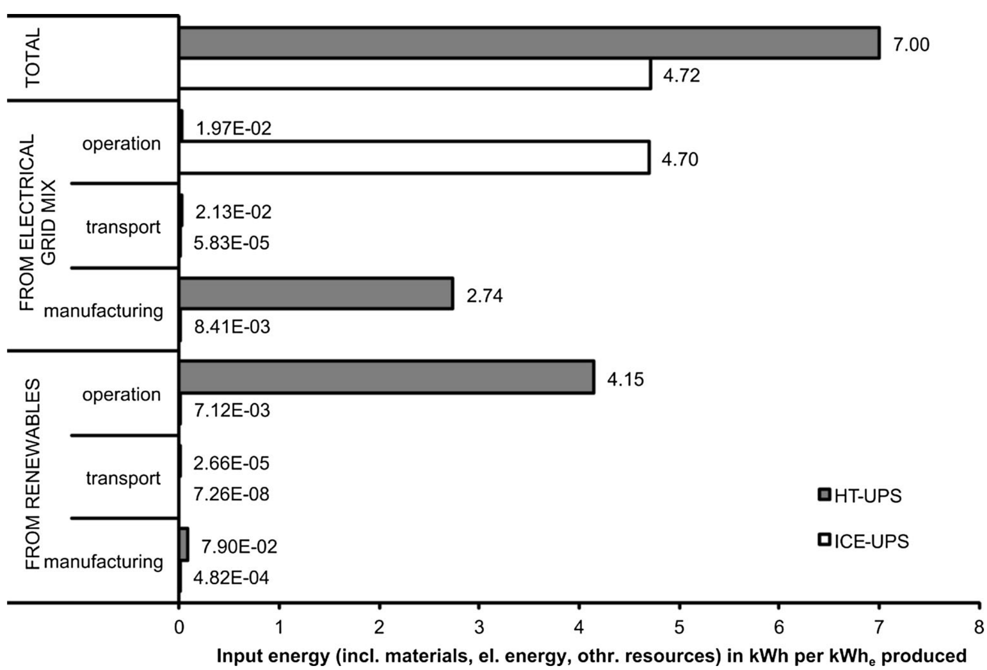


Fig. 12 Input energy values of both UPS systems per 1 kWh of produced uninterrupted electricity produced

Operation phase primary-energy-to-electricity conversions are similar for both systems and amount to 4.70 kWh/kWh_{el} for ICE-UPS and 4.17 kWh/kWh_{el} for HT-UPS system.

5 Conclusions

A hydrogen technology-based UPS system's environmental impacts were analysed with the LCA method. Life-cycle energy balance was calculated, and comparison to an ICE-based UPS was made. The study shows the hydrogen system's potentials to introduce RES in an advanced electric grid, which could reduce environmental impacts of electricity production and distribution.

The results show that

- Due to electrolyser's relatively higher power conversion capacity and subsequently its larger size compared to the fuel cell, electrolyser has the highest environmental impacts in terms of GW, AD and A when compared to fuel cell and storage tank in the HT-UPS system.
- Most environmental impacts of the HT-UPS system result from materials and parts manufacture and assembly, i.e. occur in the manufacturing phase of the HT-UPS's life cycle. The HT-UPS system is nearly environmentally neutral in its operation phase when powered by RES.
- 0.375 kg CO_2 eq per 1 kWh electricity is produced with HT-UPS compared to 1.190 kg CO_2 eq in the case of ICE-UPS, which makes the HT-UPS system environmentally sounder in terms of GW. The HT-UPS also has lower environmental impacts in terms of AD and A, but higher impact in terms of E, mostly due to large quantities of steel used to manufacture the storage tank.
- The analysis of life-cycle energy balance shows that both systems' manufacturing phase has a considerable impact on their EROI. Considerably higher energy inputs in HT-UPS's manufacturing phase make its EROI lower than that of the ICE-UPS even though the former has slightly better energy conversion efficiency in its operation phase.

HT-UPS systems as presented in this paper are applicable where RES of intermittent nature are available. The studied system's overall energy conversion efficiency and EROI are relatively low, but this study has shown that it has a lower environmental impact compared to the studied conventional ICE-UPS system in all but one impact category. In contrast to the ICE-UPS, the HT-UPS is powered by RES electricity and is also able to store it in times of excess production. The advantages of the ICE-UPS system, on the other hand, are its maturity, smaller size and lower price, but since most of its environmental impacts result from combustion of carbohydrates, its potential to lower its environmental impacts seems very limited.

Regarding the intensive ongoing R&D efforts in HT, motivated also through EU research programs, both their production and operation energy efficiencies are expected to improve. At the same time, the prices will very likely drop and lifetimes prolong. Therefore, it seems that HT may play an important role in energy systems of the future.

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